Global Change and Water Resources in the Mediterranean Mountains: Threats and Opportunities

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Abstract: The Department of Geoenvironmental Processes and Global Change (DGPGC) at the Pyrenean Institute of Ecology – CSIC (Spanish Council for Scientific Research) has been doing research on Environmental Hydrology at various spatial and temporal scales since 1990. Hydrological consequences of land cover change in mountain headwaters have proved to be complex and scale dependent. At plot scale, abandonment of traditional cultivation practices in the valley slopes had the consequence of decreasing runoff production and soil erosion and sediment yield, which were more pronounced as the revegetation process progressed. At catchment scale the differences are smaller, because part of the water that infiltrates into the soils in the vegetated areas reappears later in lower parts of the catchment. An important effect of revegetation at catchment scale is the attenuation of the catchment's response to any precipitation event (except the most extreme ones), resulting in less torrential behaviour. A decrease in total water yield has also been observed in the long term evolution (1945-1995) of discharge series in the Central Pyrenees basins, during a period in which no significant decrease of precipitation has been recorded. We attribute this trend to the process of revegetation after farmland abandonment. Changes have been found also on the monthly discharge regimen, as well as on the frequency of high flows, which decreased during the studied period. All this changes have increased the stress on water resources management, as shown by changes in reservoir management practices. We question whether we will be able to satisfy water demands in the near future, considering expected changes in climate and land cover, and we show the importance of increasing research effort on water resources in global change scenarios.

1. Introduction

Water is a strategic resource in all the countries surrounding the Mediterranean basin, with many regions periodically exposed to situations of stress, like the one experienced in spring and summer 2005 in almost all Iberian regions. In this context, water resources management has gained the status of a national issue, as illustrated by intense political debate originated in recent years by the National Hydrological Plan in Spain (Marti, 2000; Embid and Gurrea,

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2004). In a context of steadily increasing water demand it is generally admitted that water availability will be one of the drivers of future economical and social development in the region. In this sense, global change scenarios are not very promising, projecting an intensification of stress conditions during the XXI Century. This is due to the combined effect of increase in temperature and reduction of precipitation in the region (Scröter et al, 2005; EEA, 2004), along with a clear trend towards extensification and land abandonment (Rounsevell et al, 2005).

Large part of these changes is expected to happen or is already happening in the mountain areas. This is particularly significant, since mountain headwaters are primary sources of water resources in the region (Thornes, 1999; García Ruiz et al, 2001). Although the signals of climate change, specially referring to precipitation decrease, are still very weak, socio-economic processes leading to land use change have been very important in mountain areas in the Mediterranean Basin. In the most developed countries of the region (those belonging to the EU) a process of land marginalisation leaded to depopulation, extensification and farmland abandonment during the last Century (Rabbinge and Van Diepen, 2000; Taillefumier and Piégay, 2003). Decreased human pressure on mountain ecosystems has had the effect of promoting natural vegetation recovery, in some parts largely helped by vast reforestation programs (figure 1).

[insert fig. 1 about here: Land use changes in the Ijuez Valley, 1957-2002]

The effects of this changes on mountain headwater catchments is yet not completely evaluated, and is a key research topic at the DGPGC (García-Ruiz et al, 2004). Various aspects of water resources research going from total water yield, timing and quality to planning and management are of interest (figure 2).

[insert fig. 2 about here: Sketch global change effects on water resources]

The DGPGC has been doing research in field Hydrology since the early 90's. Of special concern are the scale issues, and various experimental settings have been installed to assess the effect of land use change on water resources at different scales (figure 3). The methods used comprise at-point rainfall simulation, monitoring of water and sediment production at plot scale and small catchment scale, and the analysis of historical climatic and discharge records at a basin scale. The purpose of this paper is to summarize the results obtained from these studies.

[insert fig. 3 about here: Study area]

2. Results at plot scale

Studies at plot scale allow to assess the effects of different land uses on some aspects of surface hydrology, basically the generation of surface runoff and the export of solutes and suspended sediment. In the Aísa Valley Experimental Station nine plots of 10x3 m have been installed and monitored since 1992 (Lasanta et al, in press). Soil and location conditions are virtually the same, allowing to compare the results obtained from the application of different treatments to the plots. Variables measured at each plot through automatic data loggers and water samplers are rainfall, surface runoff production, suspended sediment content and solutes. The treatments reproduce traditional and modern land use practices and different states of land abandonment. Traditional rotating cereal crops are represented by two plots which are cultivated or left fallow on alternating years. A third field was cultivated under the same practice during four years, and abandoned thereafter. Traditional shifting agriculture has been reproduced in other two plots. The management consisted on burning the original dense shrub cover, using the ashes as natural fertilizer, and cultivate the plot continuously during four years, and abandoning it after that. In other plot seasonal (summer) pasture practices are reproduced, and finally in one plot the dense shrub vegetation typical of crop fields after many years of abandonment was left as control plot. Other plots are used to study the effects of forest fires, although these results are not shown here (Cerdà and Lasanta, 2005; Lasanta and Cerdà, 2005).

[insert fig. 4 about here: Results from the experimental plots -runoff, soil loss-]

The results show important differences in surface runoff production, both in average annual values and inter-annual variation (figure 4). The highest runoff coefficient, as well as the highest variance, was observed under shifting agriculture practices (median around 16%), followed by the cereal crops (11%). The runoff coefficient diminished after land abandonment in both cases, towards similar values to those of the meadow (7.5%). The lowest mean runoff, and also the lowest variance, was observed in the shrub plot (4.5%). Regarding to soil loss, the results were similar. The highest losses were observed under shifting agriculture practices (900 kg ha^{-1}) and cereal cultivation (400-700 kg ha^{-1}), with very large inter-annual differences of almost one order of magnitude between the first and the ninth deciles. Soil loss was very much reduced after abandonment in the two cases (250 and 200 kg ha^{-1}, respectively). The shrub covered plot only exported 110 kg ha^{-1} and showed very little inter-annual variation, and the meadow was very close with 180 kg ha^{-1}.

3. Results at catchment scale

Studies at plot scale are interesting because they allow the researcher a high level of control over the treatments applied. The results, however, refer only to hydrological processes that apply at point scale, like runoff production or infiltration of water into the soil. Upscaling from plot to catchment scale is thus necessary to allow for other processes to be considered, like redistribution of soil water in the unsaturated and saturated zones. New research questions can be posed, like the hydrological behaviour of headwater catchments at event and long term time scales.

Experiments with twin catchments allow to compare the hydrological behaviour of catchments with different land cover. This is the case of the catchments of the DGPGC in the Central Pyrenees, where two catchments were instrumented and monitored since 1996, representing a disturbed situation (Arnás catchment, characterized by abandoned cereal fields with different levels of vegetation cover) and a natural situation (San Salvador catchment, completely forested). Climatic and hydrological variables are automatically measured: temperature, wind speed, radiation, precipitation, discharge, groundwater level, suspended sediment, solutes and bedload (García-Ruiz et al, 2000).

The behaviour of the two catchments is highly different (figure 5). In general, the deforested catchment showed higher total discharge. More differences arise at a more detailed level. At the beginning of the season, when the water storage in the two catchments is at its minimum after the summer period, the response to a rainfall event is highly differentiated. While in Arnás catchment some discharge was observed almost for any event, in San Salvador a certain amount of rainfall was needed before the catchment started producing any runoff. This is due to the different mechanisms of runoff production in both cases, since in Arnás there are some uncovered surfaces with very low permeability in which runoff is controlled by infiltration excess (Horton runoff) (García-Ruiz et al, 2005). In San Salvador and large parts of Arnás, on the contrary, runoff is produced only by saturation excess (Dunne runoff), what requires the previous humectation of the soils (Seeger and Beguería, 2003).

[insert fig. 5 about here: Twin catchments, runoff]

At event scale, Arnás catchment responded very fast to rainfall, with high peak flows and also fast falling limb of the hydrograph. San Salvador, on the other side, responded in a more moderate way, with less spectacular peak flows and more prolonged falling limb (Seeger and Beguería, 2003).

There were also important differences between the catchments in sediment yield (figure 6). Although the total annual yield is similar (2.04 and 1.87 t ha^{-1}) there were significant differences in the importance of different transport modes. Most of the sediment (46%) was exported as suspended sediment in Arnás, solutes representing 34% and bedload being around 20% of the total Regüés et al., 2004). In San Salvador, however, most of the transport (73.5%) was done in the form of solutes, and no bedload was observed. This is related to the longer residence times of water in the soils, resulting in higher concentration of solutes.

[insert fig. 6 about here: Twin catchments, sediment yield]

4. Results at basin scale

Research at plot and catchment scale allows to gain detailed insight into the hydrological effects of land use change in the Pyrenees. In a survey about land use change in the Aragón River basin (c. 2000 km^2), comparing aerial photos from 1956-57 and today, the abandoned surface was estimated in about 22% of the total area. Of the abandoned fields, 65% of the surface is now covered by natural secondary forest or reforestation; 28% has transformed into dense shrubland; and 7% is still used as meadows or seasonal pastures. From a management point of view, an evaluation of the effect of these changes on water resources is needed at a basin scale.

Important questions at this scale are: Can we detect a trend in the availability of water resources during the last Century? If such a trend exists, can it be attributed to climate drifts, to land cover change, or to both of them? What changes can we expect in water resources availability in a near future? How can the current water management strategies deal with this changes? Analysis of historical records of climate, discharge and reservoir levels in the Pyrenees have helped to address these questions.

4.1. Total water yield

The analysis of temporal series of precipitation, temperature and discharge allowed us to determine the influence of climate and other drivers (mainly land use change) on the annual water yield (Beguería et al., 2003). Regional adimensional series were constructed from 18 weather stations and 28 gauging stations from the central sector of the Spanish Pyrenees (figure 1). A common recording period from 1945 to 1995 was used (fifty years). The regional series show the annual evolution of total rainfall and water yield (volume of water) in the region, expressed in standard deviations over the average in the period (figure 7).

[insert fig. 7 about here: Evolution of rainfall and runoff in the Pyrenees]

As it can be seen in the plot, no clear trend in precipitation is found in the period analysed, but alternated dry and wet periods instead. The relation between the two variables, however, shows important differences. Until 1975 approximately the discharge curve appeared systematically *under* the line representing the precipitation, but this relationship was inverted in the second half of the period. This suggests a gradual change in the relationship between rainfall and runoff along the study period. An attempt to relate this shift to the evolution of temperature during the same period was unsuccessful. No significant increase in water consumption occurred in the area, due to the very low population in the high valleys. The only driver that could explain the observed change in the rainfall-runoff transfer process was the change in land cover, more precisely the revegetation of vast surfaces during the period analysed.

A simple linear regression model was used to estimate the surface water losses. It was seen that the annual water yield could be predicted with good accuracy (r^2 = 0.939) from the regional annual precipitation. The analysis of the evolution of the residuals over time (figure 7) offers a way of quantifying the shift in the model produced by the change in land cover. It was found that the residuals of the regression (observed minus predicted) showed a clear downward trend during the study period, significant at a=0.99. This means that the same amount of rainfall produced significantly less water at the end of the study period than at the beginning. This loss was estimated at around one fourth (25%) during the study period, what represents a very important loss in terms of water resources.

4.2. Annual regime and flood frequency

The experience from the experimental catchments shows that not only a change in total water yield can be expected from changes in the vegetation cover, but also in the hydrological response to given events. This includes the annual timing of discharge (regime) and the frequency of high flows and flooding.

We used the regional series of precipitation, temperature and discharge to analyse the existence of trends in the monthly totals of these variables (Beguería et al., 2003; García-Ruiz et al, 2001). We used the Spearman's Rho test against a null hypothesis of a linear trend in the period 1945-1995 (table 1). The results show that there is little evidence of trends in precipitation, which only showed significant positive trends for the months of October and May, with very little increment (0.12 and 0.39 standard deviations, respectively). The case of temperature was similar, with significant trends of opposite sign only in January and April (0.58 and -0.39 sd). Discharge, on the contrary, showed significant decrease in eight months, with values ranging from -0.37 to -0.63 sd. The changes were concentrated in the periods of spring - early summer and autumn.

[insert table 1 about here: Monthly trends in precipitation, temperature and discharge]

For analysing the existence of changes in the frequency of high flows and flooding we calculated the discharge corresponding to different return periods (extreme quantiles) using two data sets from the periods (1) 1945-1978 and (2) 1978-1995 (table 2). Both data sets included approximately equal number of years in which rainfall was higher and lower than the average . The quantiles were calculated using partial duration series sampling on discharge series, and adjusting the resulting samples to Generalized Pareto distributions using the method of L-moments (see Beguería, 2005). The results are very different in the two analysed periods and for all gauging stations, indicating a decrease in the frequency of high flows that is reflected in lower expected highest discharges for the same return periods (García-Ruiz et al, 2001).

[insert table 2 about here: Return period of high flow]

4.3. Induced changes in reservoir management strategies

We have seen so far that significant alteration of total water yield, annual regime and frequency distribution of discharge has occurred in the Pyrenees during the last decades, and that this changes can be attributed to the abandonment of cultivated land and revegetation over large surfaces. This fact can have great impact on water resources availability for human use, since discharge from virtually all Pyrenean rivers is stored in reservoirs downstream and distributed for irrigation, industrial and urban use.

We addressed this question by analysing management patterns of this reservoirs. Here we present the example of the Yesa reservoir in the Aragón River. The Yesa reservoir was built in 1959, with a capacity of 470 hm^3. The water is derived through the Bardenas canal, and it is mainly used for irrigation in the Bardenas sector, which receives a slightly increasing amount of water every year.

We analysed the storage regime of the reservoir through monthly series of water level, input and output dicharge (López-Moreno et al, 2004). PCA analysis on different years regimes showed two types of management. In ordinary years, which predominated in the first two decades of operation of the reservoir, high storage levels were reached at the beginning of the winter, grace to autumn rainfalls usual under Mediterranean climate. The managers then released as much water as it entered the reservoir keeping a safety margin of about 20% of the reservoir capacity, and completed the filling to the maximum capacity in late spring.

The situation predominating in the last two decades, however, was different. Due to diminished discharge, specially during the autumn high flows, the managers needed to keep infilling the reservoir almost during the whole season. Some years even the maximum storage levels were not reached at all in the beginning of the summer. This example demonstrates that the observed hydrological changes have had an impact also at management level. Since the water derived toward the Bardenas Canal has increased in the last few years, this means that a lower discharge is released toward the Aragón River (López-Moreno et al., 2004).

5. Discussion and conclusions

We have found a significant decrease in water resources in the Pyrenees during the second half of the XXth Century, together with changes in the monthly regime and in the frequency of high flows. We attributed this trends to changes in land cover undergone in the study area during that period, including land abandonment and vegetation recovery in a vast part of the Pyrenees. This hypothesis was corroborated at different scales, from direct experimentation at plot scale to observation at both catchment (through the comparison of twin catchments) and basin scales (through observation of trends in time series of concerned variables).

We also showed that the current situation is not critical, since reservoir management strategies have been flexible enough to compensate for this changes and feed the current water demand. However, a shift has been detected in reservoir management towards more stressed situation, reflected in longer infilling periods to reach the same amount of water storage. A pertinent question is whether the system will be also sustainable in the future, when added stress in the form of climate change will reduce water yield even more.

The process of vegetation recovery is expected to continue in the near future, although most probably the rate will decrease with respect to that observed in the first decades after abandonment. Climate change is expected to increase water stress through reduction in precipitation and increase in potential evapotranspiration. However, we do not know with certainty what the effects of climate change will be in mountain regions, that can differ from the general trends expected in the Mediterranean area. Thus, more research is needed for estimating water resources generation in headwater catchments in scenarios of global change.

Other aspects arise from the experimental and observational settings at detailed scale. For example, it has been seen that farmland abandonment has the immediate effect of reducing soil loss and sediment delivery to values more close to densely vegetated areas. This has been shown both at plot and small catchment scale. Besides the conservation of soil resources, this has the effect of reducing the sediment load in mountain rivers, which in turn has important consequences on the river system (Beguería et al., in press). A beneficial effect of this process are lower rates of reservoir siltation, which results in enlarging the lifespan of reservoirs (López-Moreno et al, 2002).

Also, observational experiments in twin catchments have shown that revegetation leads to decreased torrential behaviour of mountain streams, resulting in a less hazardous environment.

Up to now no complete assessment has been made on the consequences of global change for water resources in the Mediterranean area. Integrated management plans should consider both the effects of climate and land cover changes, and not only on total water yield but also on other aspects like monthly regime, torrentiality, flood frequency or sediment yield. As it has been shown here, land cover can have a very significant role on headwater catchments hydrology, and thus on global water resources in Mediterranean environments.

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Tables

Table 1.Monthly trends of precipitation, temperature and discharge in the Central Pyrenees in the period 1945-1995, from regional time series over 18 and 28 climatic and gauging stations. The magnitude of the trend is expressed in standard deviations over the average in the same period.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Precipitation	0.09	-0.23	-0.44	0.29	0.12*	0.02	0.34	-0.01	-0.01	0.39*	0.30	0.20
Temperature	0.58*	0.28	0.17	-0.39*	0.03	-0.21	0.16	0.19	-0.32	-0.09	0.10	0.37
Discharge	-0.17	-0.42*	-0.43	-0.62*	-0.75*	-0.46*	-0.37*	0.01	-0.60*	-0.52*	-0.63*	-0.17

*: trend is significant at a = 0.95

Table 2. Estimated maximum discharge for different return periods at several gauging stations in the Pyrenees (m^3 s^{-1}), calculated for two different registering periods.

	Period 1945-1978				**Period 1979-1995**			
	1 year	**5 years**	**10 years**	**25 years**	**1 year**	**5 years**	**10 years**	**25 years**
Aragón R. at Jaca	42	160	200	263	27	99	124	165
Gállego R. at Anzánigo	119	422	496	596	76	215	264	340
Ésera R. at Eriste	49	114	138	175	32	64	79	105
Vero R. at Lecina	13	34	38	42	6	18	22	26

Figure captions

Figure 1. Land cover changes in the Ijuez between 1957 (*a*) and 2002 (*b*). The abandonment of cultivation fields in the valley slopes was generalized in the valley during the 50's of the last Century, and was followed by a process of natural and artificial revegetation.

Figure 2. Effects of global change on various aspects of water resources.

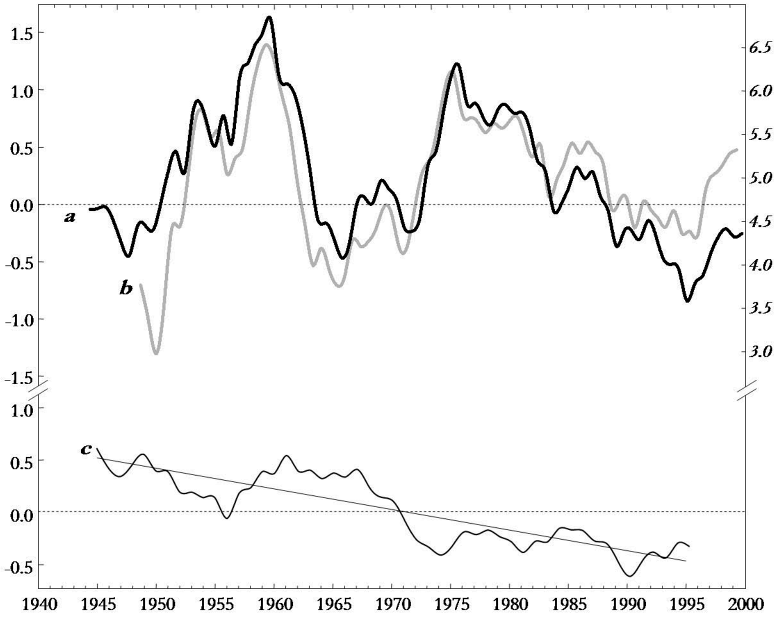
Figure 3. Multi-scale approach to field Hydrology studies: location of the different study areas. Contour of the Central Pyrenees basins analysed in the study. Also shown are: 'Valle de Aísa' experimental station (*a*); 'Loma de Arnás' experimental catchment (*b*); 'San Salvador' experimental catchment (*c*); climatic observatories (*d*); gauging stations.

Figure 4. Results from different treatments at plot scale in the Valle de Aísa experimental station. Surface runoff, in % of the precipitation (*a*); annual soil loss, in kg ha^{-1} (*b*). Box plot: first decile, 10% (c), first quartile, 25% (d), second quartile or median, 50% (e), mean (f), third quartile, 75% (g), ninth decile, 90% (h). The treatments are (see explanation in the text): traditional rotating cereal crop, cultivated (1) and fallow (2) phases; abandoned cereal crop (3); shifting agriculture (4); abandoned shifting agriculture (5); meadow (6); shrubs (7).

Figure 5. Hydrographs observed at Arnás (*a*) and San Salvador (*b*) experimental catchments (October 1999 to February 2000). Discharge is expressed in l m^{-2} to compare between the two catchments of different size, and also to compare with the observed rainfall (in the same units).

Figure 6. Sediment yield observed at Arnás (*a*) and San Salvador *(b)* experimental catchments, hydrological year 1999-2000. Suspended sediment (1), solutes (2) and bedload (3).

Figure 7. Regional time series of discharge (*a*) and precipitation (*b*) in the Central Pyrenees basins. Units are standard deviations over the average in the period 1945-1995. Secondary units (right axis, in italic font) is the total annual water yield of the Central Pyrenees basins, in hm^3 x1000. Below (*c*) are shown the residuals from estimating the annual water yield (a) upon total rainfall (*b*), and minimum-squares adjusted linear trend.



1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
a
b
1.0
0.5
0.0
-0.5
c
1940
1945
1950
1955
1960
1965
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1975
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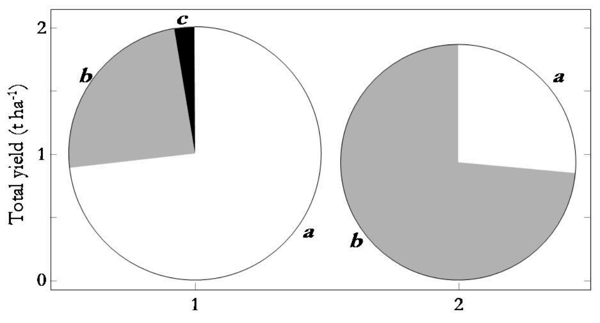
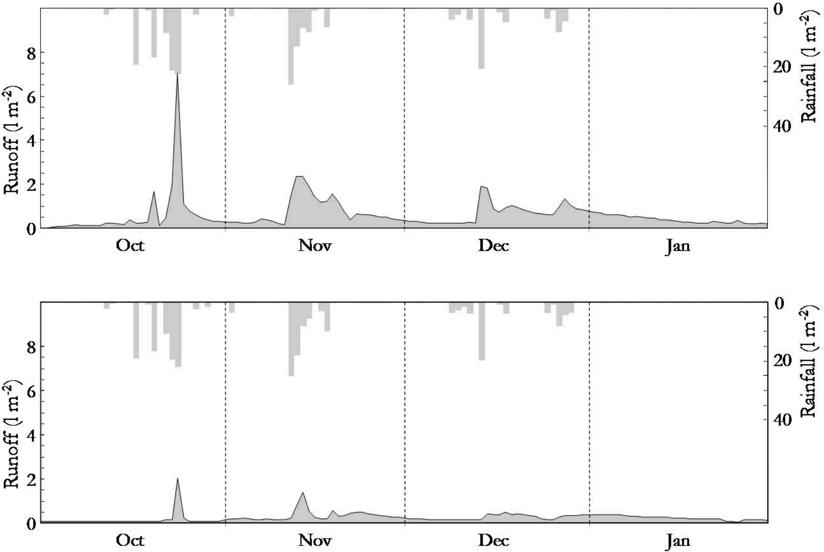
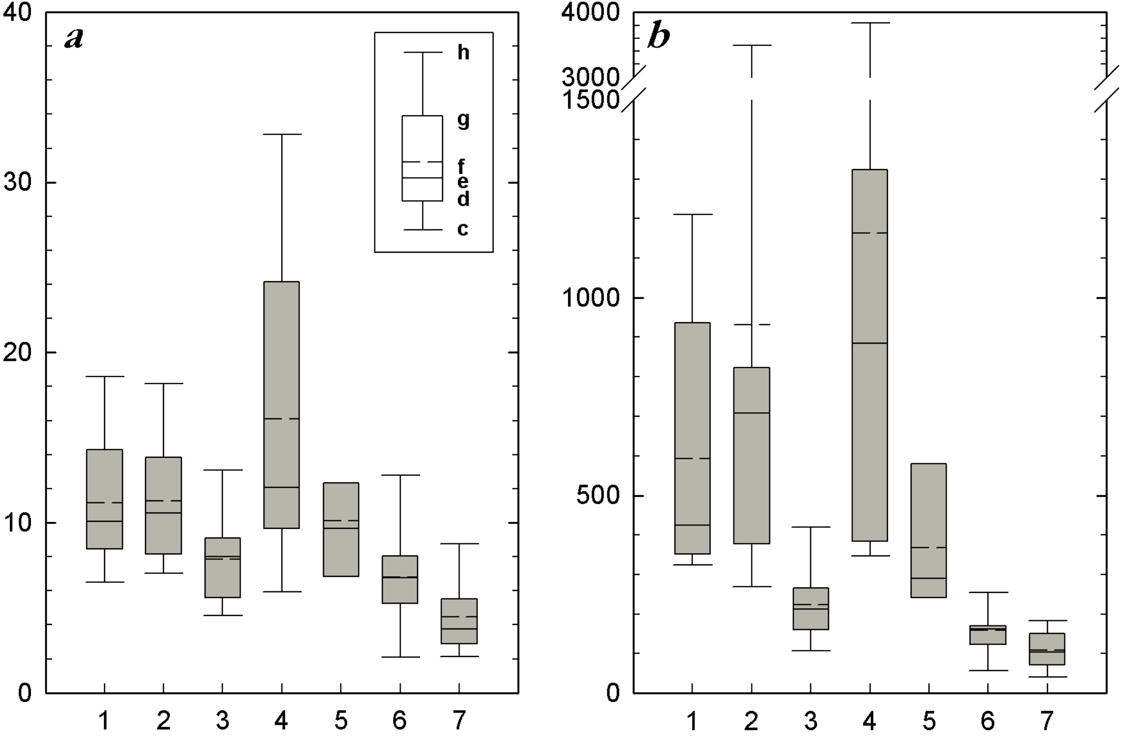


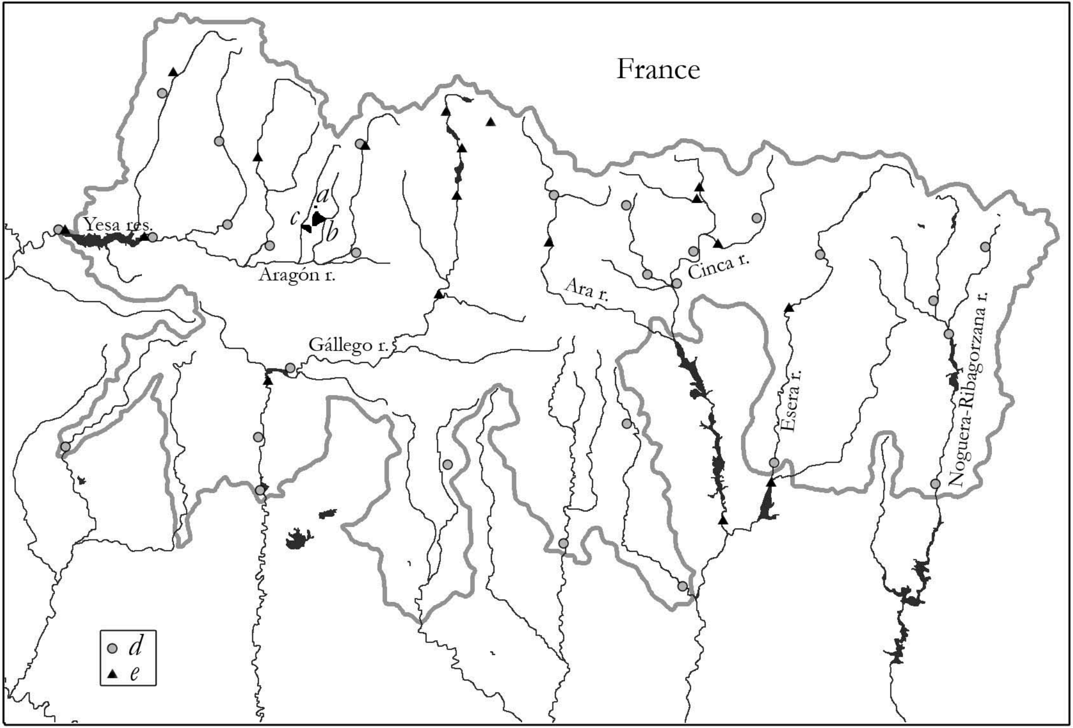
Total yield (t ha-1)
2
1
0
c
b
a
a
b
1
2



Runoff (l m-2)
Rainfall (l m-2)
0
2
4
6
8
20
40
Oct
Nov
Dec
Jan
Runoff (l m-2)
Rainfall (l m-2)
Oct
Nov
Dec
Jan



a
b
h
g
f
e
d
c
40
30
20
10
0
4000
3000
1500
1000
500
0
1
2
3
4
5
6
7


France
Yesa res.
a
c
b
Aragón r.
Ara r.
Cinca r.
Gállego r.
Esera r.
Noguera-Ribagorzana r.
d
e

a

b